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# Simulation Studies of Cyanide-Caused Cardiac Toxicity

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**14. ABSTRACT**

A series of computer studies showing the effect of cyanide (CN) on the electrophysiology of cardiac tissue is presented. A mathematical model of the electrophysiology of cardiac tissue, with initial and boundary conditions based on experimental data from studies using CN as metabolic blockers from the literature, was used to simulate changes in the electrical activity of the heart. Emphasis was on the modulation of ion concentrations in the cells, changes in current magnitudes, and the activation of currents that are dormant under normal circumstances.

These calculations showed for the first time: (1) disturbance of the energy homeostasis and ion concentrations in cardiac tissue due to CN results in the reversal of the direction from the normal and change in magnitudes of cellular membrane currents. These, in turn, change the morphology of the action potential and the electrocardiogram (ECG). This is the initial step leading to ventricular fibrillation, the usual endpoint in the effect of CN on the heart. (2) CN causes cell swelling and hemorrhaging in cardiac tissue. Cell swelling activates chloride membrane currents affecting homeostasis of the tissue. These effects were shown to be important for the electrical state of the CN-affected tissue and were included for the first time in a model of CN-affected cardiac tissue. (3) The calculations reproduced aspects of the changes in an ECG of a subject under the effect of a lethal dose of CN. (4) The obtained results suggest and define the characteristics required of a pharmacological intervention needed to overcome or reverse CN poisoning, of vital importance for development of therapeutics for force protection. Primarily, such intervention needs to reduce the calcium overload of the cardiac cell, restore the depolarizing sodium current, and alleviate the accumulation of potassium ions exterior to the cell.

**15. SUBJECT TERMS**

computer simulation, cardiac toxicity, cyanide

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# 1. Introduction

Cyanide (CN) is one of the most potent poisons used in warfare since ancient times. Development of effective antidotes for the warfighter is still a work in progress because many of the CN-affected cellular processes are not completely understood. These processes can now be mathematically modeled, based on experimental measurements, and the effects of changes in cellular parameters due to the presence of threat agents predicted. Only recently, with scalable computers coming online, has computational capability improved to the point where such simulations could be attempted. This report demonstrates the power of in silico (computational) experiments as a cost-effective, ancillary means of advancing the development of threat agent antidotes that is an essential part of force protection. We believe that this new approach will have a major impact on future therapeutic developments (see also Zoltani et al., 2003, 2004a, 2004b, and 2004c).

The strategy adopted was to use tissue parameter values in the mathematical simulations available from experimental investigations where CN was used as a metabolic blocking agent. The deviations from the baseline morphology in the calculated action potential (AP), expressing the voltage in the tissue as a function of time, and the mathematically-generated electrocardiogram (ECG), was related to and correlated with the measured tissue parameters. This gives a direct indication of the effects that have the strongest influence on the deviation of electrical state of the tissue from baseline and are the best candidates for pharmacological intervention in case of CN intoxication.

# 2. Effect of Cyanide on Cardiac Tissue

Dose-dependent heterogeneity marks the deposition of CN in cardiac tissue. Histological changes include cell swelling and hemorrhaging. CN has a strong attraction for iron ions, and its deposition prevents the transfer of electrons to molecular oxygen. Though there is oxygen available, it cannot perform the normoxic function in the adenosine triphosphate (ATP) generation needed by the tissue. The tissue becomes oxygen "starved," resulting in the modulation of the energy homeostasis. Initially, glycolysis attempts to replenish the ATP, the energy source, but the replenishment is short lived. The whole tissue substrate changes; lactic acid and catecholamines are formed. The stage is set for changes and deviation from the norm in the electrical activity of the tissue.

One of the first manifestations of the changed electrophysiology is bradycardia that may soon change to Torsade de Pointes and possible culmination in ventricular fibrillation. On the ECG, the P-wave, the atrial depolarization, is eliminated. ST-segment deviation, usually a rise in the

slope, becomes noticeable, followed by modulation of the T-wave. The changed morphology is expressed in steepening and coalescing of the QRS and the T-waves. A J-wave becomes noticeable. Additional details are given in Katzman and Penny (1993) and Wexler et al. (1947).

On the cellular level, changes in the ion concentrations become important, especially calcium overload of the cell and increase in the extra cellular potassium concentration, $[K^+]_o$. The cell's energy homeostasis (Balaban, 2002) is profoundly disturbed, and several compensatory membrane currents are activated and others diminished. Three of the most important ones are the ATP-dependent $I_{KATP}$ (Elliott et al., 1989), the osmotic swelling-activated $I_{Cl,swell}$, and the calcium-dependent $I_{Ca(L)}$. The disequilibrium in the membrane currents caused by the CN has grave implications for the cell's electrophysiology. CN-caused cardiac toxicity shares some commonality with ischemia but is different in the level of acidity of the tissue and the nature of some of the activated currents. A number of ancillary effects, including enhanced catecholamine (CA) secretion, the effect of the increase in free $Mg^{2+}$, and pH changes, are not addressed in this report, but we note that CA binds to $\alpha$ and $\beta$ receptors that affect membrane currents. Additional details are given in Baskin and Brewer (1997), Baskin et al. (2004), Leimdorfer (1950), and Van der Heyden et al. (1985).

## 3. Computer Model

The effect of the presence of CN in the tissue was modeled by changing the tissue parameters to those measured in CN-caused metabolic blockade of cardiac tissue available in the open literature and including the currents activated under these conditions. Two of the more important ones for this model are the activation of $I_{KATP}$ due to decline in the ATP stores and $I_{Cl,swell}$ when the cell volume is modulated. Change in cellular ion concentrations is also an important aspect of CN toxicity. Calcium overload causes the activation of $K^+$ channels (Inoue, 1998). Rise in $[Na^+]_i$ and $[Ca^{2+}]_i$ enhances the $i_{Ks}$ current that is activated at voltage values much higher than for $i_{Kr}$. $i_{Kr}$ is reduced by acidification and the presence of external divalent cations, noticeable in CN-affected tissue.

For these numerical simulations, cardiac tissue cells of three kinds were considered: epicardial, midmyocardial, and endocardial (representing the ventricular wall). The important distinction among these cells for these calculations is in the value of the maximum cell conductance. The model of Vandenberg et al. (1997) for osmotic swelling-activated chloride current was modified and incorporated into the simulations. It accounts for the expression of some of the changes in the membrane currents caused by CN-caused lesions (Suzuki, 1968). Cell swelling contributes to the rise of the resting membrane potential and the shortening of the AP.

For the calculations reported here, a monodomain approach was adopted with fiber orientation (one of the diffusion matrix entries) assumed to be uniform. The propagation of the AP was based on the following cable equation:

$$\frac{\partial V}{\partial t} = -I_{ion}/C_m + D\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right). \tag{1}$$

In this equation, $V$ is the membrane voltage and $I_{ion}$ is the transmembrane ionic current, mainly made up from the sodium, potassium, calcium, and chloride currents, and pumps and exchangers. $D$ is the diffusion constant and $C_m$ the membrane capacitance. Appended are the gating variables of the ionic channels and equations for the change of the ion concentrations. No flux boundary conditions were used. The computational domain consisted of a fiber of 165 cardiac cells incorporating the regional differences of the tissue parameters in the ventricular wall. The signal propagation was described by a reaction diffusion equation. Explicit Euler method is adequate for the solution algorithm, although Crank-Nicholson can give more accuracy.

After determining the baseline in these simulations, the approach was to vary the ion channel conductivities thought to be affected in CN-affected tissue. In addition, a series of simulations were performed increasing the extra cellular potassium concentration, the calcium concentration in the cell, and the internal sodium level. Two additional currents, the ATP dependent potassium current and the cell volume dependent chlorine current, were activated in the simulation of severely-affected tissue. Using the conditions of table 1, first a baseline AP and then a pseudo-ECG were calculated. The former used the Luo-Rudy model of the cellular processes described in Ferrero et al. (1996) and Shaw and Rudy (1997). A pulse of 200 mA/cm$^2$ of 0.5-ms duration initiated the AP.

Table 1. Initial values.

| Model Quantity | Baseline (mM) | CN-Affected Cell (mM) | Ischemia (mM) |
|---|---|---|---|
| $[Na^+]_i$ | 10.0 | Incr. ~2.5 x | 10 - 20 |
| $[Na^+]_o$ | 145.0 | 134.0 | 140.0 |
| $[K^+]_i$ | 150.0 | 125.0 | 125.0 (acidic) |
| $[K^+]_o$ | 4.0 | 10.0 | 4 -16 |
| $[Ca^{2+}]_i$ | 0.0003 | Incr. >3 x | 0.0003 – 0.0009 |
| $[Ca^{2+}]_o$ | 1.8 | 2.0 | ~2.0 |
| [ATP] | 5.0 | 3.0 | 3.0 < |

Using the formulation of Plonsey and Barr (2000) with the pseudo-ECG electrode at 2 cm from epicardium, the extra cellular unipolar potential generated by the fiber in the surrounding field was calculated from

$$\Phi_e = \frac{a^2 \sigma_i}{4\sigma_e}\int\left(-\nabla V_m\right)\left[\nabla \frac{1}{r}\right]dx, \tag{2}$$

where $a$ is the radius of the fiber, $r$ is the distance from the source to the field point, $V_m$ is the

transmembrane potential, and $\sigma_i/\sigma_e$ is the ratio of the intracellular to the extra cellular conductivities.

The mathematically-generated ECG was calculated on a strip of cardiac tissue made up of three types of cells: endocardial, midmyocardial, and epicardial. A distinctive difference among these cells is the maximum value of the channel conductance for the $i_{Kr}$ and the $i_{Ks}$ currents. The conductance ratios for these cells were set at 11:1, 4:1, and 35:1, respectively, following experimentally-obtained values (Viswanathan and Rudy, 2000).

## 4. Results

The ECG and the AP morphologies are markers of the electrophysiological state of cardiac tissue. The baseline, figure 1 with the insert showing the epicardial AP, was the starting point in these simulations. The parametric values of the substrate were modified within the guidelines of table 1, using data from Carmeliet (1999), Antzelevitch and Zygmunt (2003), Lukas and Antzelevitch (1993), Mejia-Alvarez and Marban (1992), and Ju and Allen (2003), in a series of calculations.
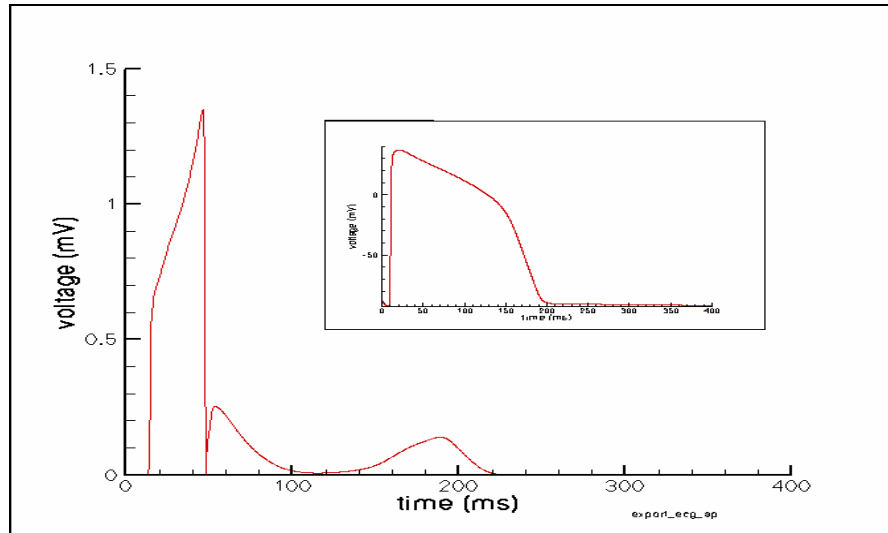


Figure 1. The baseline mathematically-generated ECG of the cardiac tissue with AP shown in the insert.

Figure 2 shows the effect of CN intoxication on the AP of ventricular tissue. Notable are the shortened cycle length (CL), a sign of tachycardia, the lowering of the wave amplitude, and the rise of the resting potential. Figure 3 shows the effect on the ECG, whose morphology has been drastically altered. A T-wave as a separate entity is no longer in evidence, the shape of the QRS portion has been altered, and the peak has been halved. With the chloride current activated, a further deviation of the shape of the wave from the norm occurs (figure 4).
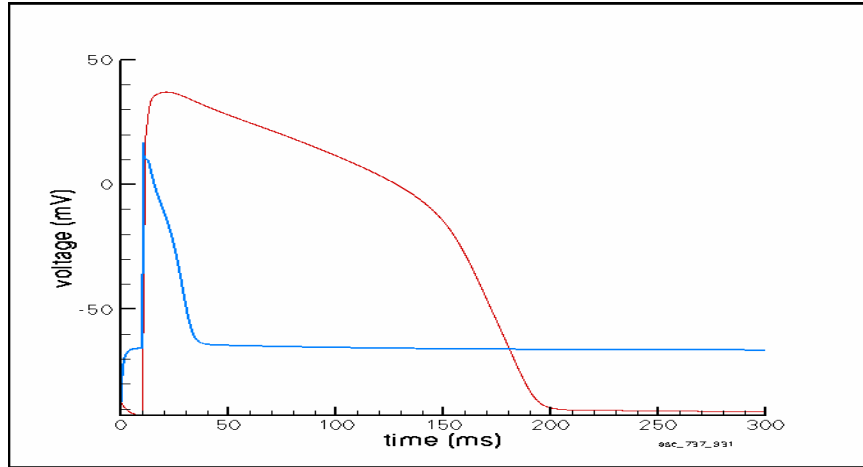
Figure 2.  CN notably shortens the CL of affected tissue (blue trace) in comparison with the baseline (red trace).
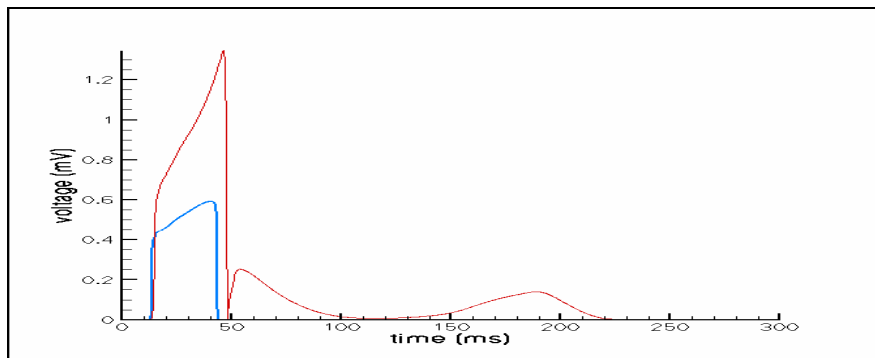


Figure 3.  Simulated ECG (blue trace) of severely CN-affected cardiac tissue. $[Ca^{2+}]$ = 0.0009, [ATP] =1.0, and $K^+_o$ =12.0 mM/L. The baseline is shown in red.
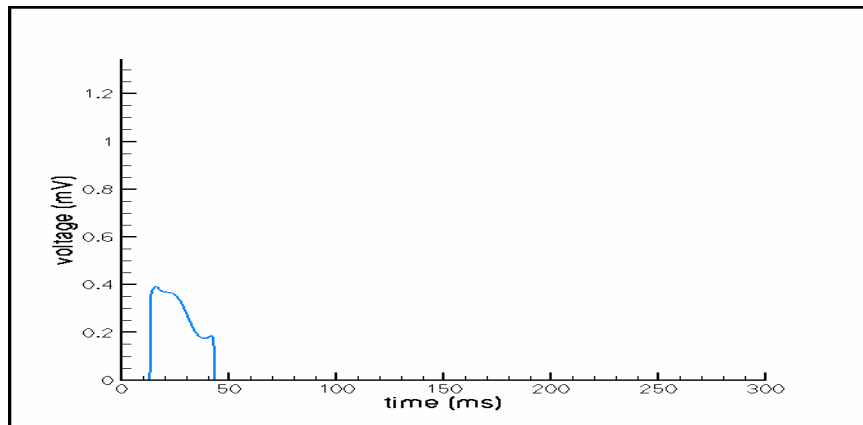


Figure 4.  When the normoxic dormant currents are activated, further morphological changes in the ECG are evident.

The calculations reproduced aspects of the changes in an ECG of a subject under the effect of a lethal dose of CN (figure 5 [Wexler et al., 1947]).  The change in the morphology is reproduced in figure 6.
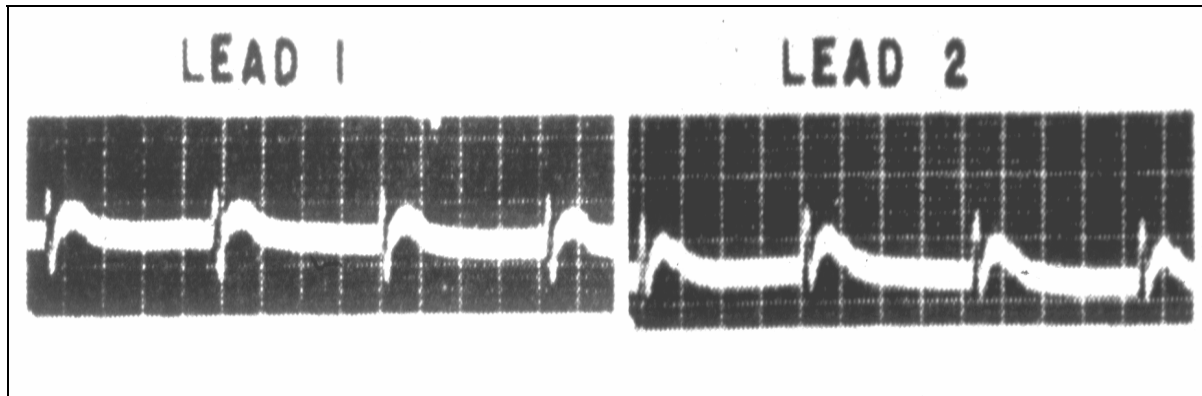
Figure 5. ECG from a CN-intoxicated individual from Wexler et al. (1947).
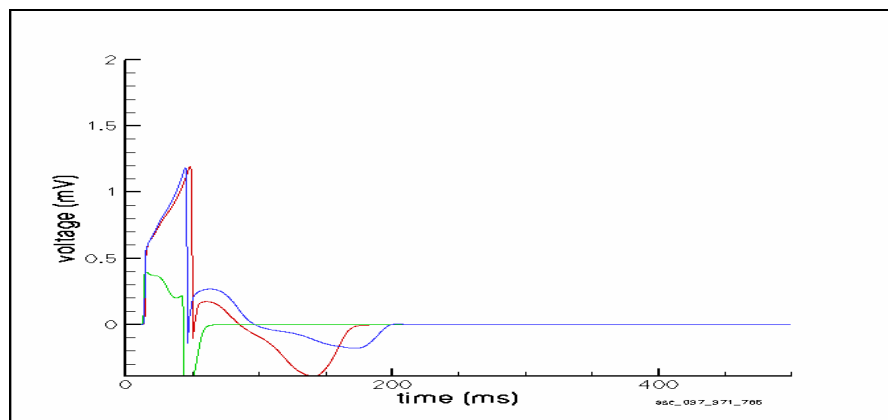


Figure 6. The effect of calcium-overload, reduced availability of ATP, and high
external potassium concentration.

A series of simulations to determine the effect of the individual parametric changes are summarized in figure 6, concentrating on the effect of intracellular calcium overload, reduced availability of ATP, and high external potassium concentration. The red trace shows the effect of a 50% overload of internal sodium. The blue curve represents potassium and calcium overload. The green ECG trace shows the effect of the activation of the chloride channel under ion concentration overload conditions. The reversal from normal direction of the membrane currents was noted in the data.

Disturbance of the energy homeostasis and ion concentrations in cardiac tissue due to CN results in the reversal of the direction from the normal and change in magnitudes of cellular membrane currents. These, in turn, change the morphology of the AP and the ECG. This is the initial step leading to ventricular fibrillation, the usual endpoint in the effect of CN on the heart. Several of the membrane currents reverse direction under these tissue conditions. The negative trending T-wave in the ECG indicates pathological behavior and abnormal repolarization of the ventricle.

CN causes cell swelling and hemorrhaging in cardiac tissue. Cell swelling activates chloride

membrane currents affecting homeostasis of the tissue. These effects were shown to be important for the electrical state of the CN-affected tissue and were included for the first time in a model of CN-affected cardiac tissue.

Pharmacological intervention can reverse the effect of CN intoxication, as shown in figures 7–9. Restoration of the cell's energy source, the ATP concentration, and blocking calcium accumulation within the cell are primary objectives of therapeutic strategies.
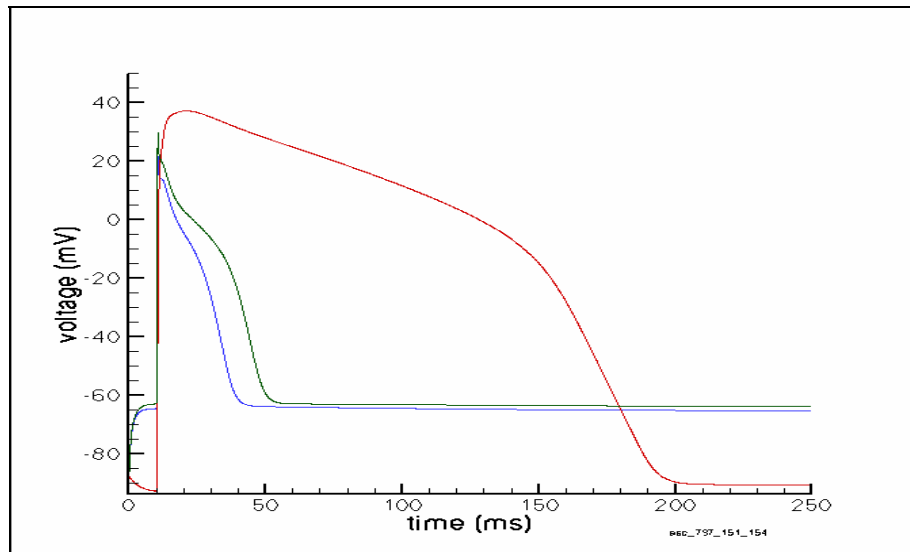


Figure 7. The sodium concentrations returned to normal, and, with internal calcium at 0.0004 mM/L, the CL is improved, but tachycardia still is in evidence.
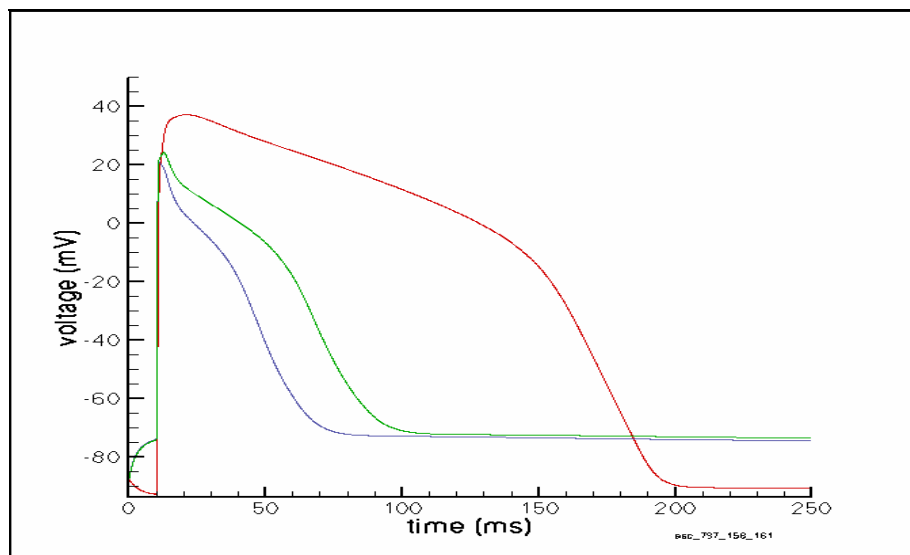


Figure 8. Elimination of the exterior potassium overload helps (green curve), but baseline behavior is not achieved.
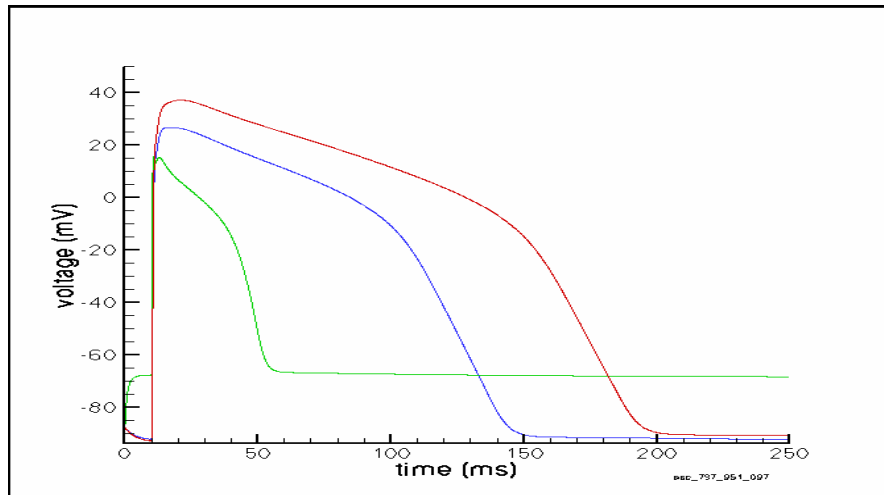
Figure 9. Simulated pharmacological intervention: the red trace shows the
baseline. The blue trace shows the case with ion concentrations restored
except for sodium, showing a 50% cell overload.

## 5. Discussion

Exposure to CN has immediate consequences on the electrophysiology of the heart. This computational study focused on several of the determining factors characterizing the morphology of the AP and the ECG.

CN changes the energy homeostasis and ion concentrations, and causes the activation of several otherwise dormant membrane currents. These include $I_{KATP}$, $I_{CL,swell}$, and the throttling of $I_{Ca(L)}$. Their inclusion into the model presented is vital for the simulation of the CN-caused ECG modulation. Considerable refinements in the results were possible by inclusion into the model of the swelling-activated chloride current. The simulation was able to approximate changes observed in the ECG of a subject under CN toxicity. The calculations showed the rise in the resting voltage and demonstrated how it could be restored to baseline. Means of recapturing the width of the AP post-CN-modulation, important for preventing arrhythmia, was also illustrated. These approaches also allow modification of the ST segment and J-wave modulations caused by CN. The ST denivelation seen in the experimental data was clearly reproduced in the model figure 3. The QRS widening and modulation of the wave is also seen in the calculational results (e.g., figure 4). Parametric changes of the substrate, as shown in figure 7, can change the morphology of the AP and the electrophysiology of the tissue.

In silico techniques are powerful ancillary tools for the understanding of the modulation of cellular processes by threat agents. The results of this study narrow the search on the requirements on the means of pharmacological intervention to counter the effect of CN-caused cardiac toxicity. Of special importance may be the restoration of ATP, potassium, and calcium concentrations in the ventricular cells, increase of the level of $I_{Ca(L),}$ and modulating of $I_{CL,swell}$.

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